

# FINAL REPORT OF THE SPACE SHUTTLE PAYLOAD PLANNING WORKING GROUPS

MATERIALS PROCESSING  
AND  
SPACE MANUFACTURING

MAY 1973

NATIONAL AERONAUTICS & SPACE ADMINISTRATION  
GODDARD SPACE FLIGHT CENTER  
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## GLOSSARY

<u>Abbreviation</u>	<u>Description</u>
ARC	Ames Research Center
ASTP	Apollo - Soyuz Test Program - US/Russian Manned Mission
DNA	Deoxyribonucleic Acid
GFE	Government Furnished Equipment
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
MSC	Manned Spacecraft Center
MSFC	Marshall Space Flight Center
MTL	Materials Testing Lab
TRW	TRW, Inc.

FINAL REPORT  
OF THE  
SPACE SHUTTLE  
PAYLOAD PLANNING WORKING GROUPS

Volume 9  
Materials Processing  
and  
Space Manufacturing

MAY 1973

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Greenbelt, Maryland 20771

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### FOREWORD\*

In January 1972 the United States decided to develop a new space transportation system, based on a reusable space shuttle, to replace the present expendable system.

By January 1973 planning had progressed to the point that through the European Space Research Organization (ESRO) several European nations decided to develop a Space Laboratory consisting of a manned laboratory and a pallet for remotely operated experiments to be used with the shuttle transportation system when it becomes operational in 1980.

In order to better understand the requirements which the space transportation must meet in the 80's and beyond; to provide guidance for the design and development of the shuttle and the spacelab; and most importantly, to plan a space science and applications program for the 80's to exploit the potential of the shuttle and the spacelab, the United States and Europe have actively begun to plan their space programs for the period 1978-1985, the period of transition from the expendable system to the reusable system. This includes planning for all possible modes of shuttle utilization including launching automated spacecraft, servicing spacecraft, and serving as a base for observations. The latter is referred to as the sortie mode. The first step in sortie mode planning was the Space Shuttle Sortie Workshop for NASA scientists and technologists held at the Goddard Space Flight Center during the week of July 31 to August 4, 1972. For the purposes of that workshop, shuttle sortie missions were defined as including those shuttle missions which employ observations or operations (1) from the shuttle itself, (2) with subsatellites of the shuttle, or (3) with shuttle deployed automated spacecraft having unattended lifetimes of less than about half a year.

In general the workshop was directed towards the education of selected scientific and technical personnel within NASA on the basic capabilities of the shuttle sortie mode and the further definition of how the sortie mode of operation could benefit particular disciplines. The specific workshop objectives included:

- Informing potential NASA users of the present sortie mode characteristics and capabilities
- Informing shuttle developers of user desires and requirements
- An initial assessment of the potential role of the sortie mode in each of the several NASA discipline programs
- The identification of specific sortie missions with their characteristics and requirements

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\*Reprinted from the volume entitled "Executive Summaries".

- The identification of the policies and procedures which must be changed or instituted to fully exploit the potential of the sortie mode
- Determining the next series of steps required to plan and implement sortie mode missions.

To accomplish these objectives 15 discipline working groups were established. The individual groups covered essentially all the space sciences, applications, technologies, and life sciences. In order to encourage dialogue between the users and the developers attendance was limited to about 200 individuals. The proceedings were, however, promptly published and widely distributed. From these proceedings it is apparent that the workshop met its specific objectives. It also generated a spirit of cooperation and enthusiasm among the participants.

The next step was to broaden the membership of the working groups to include non-NASA users and to consider all modes of use of the shuttle. To implement both objectives the working group memberships were expanded in the fall of 1972. At this time some of the working groups were combined where there was appreciable overlap. This resulted in the establishment of the 10 discipline working groups given in Attachment A. In addition European scientists and official representatives of ESRO were added to the working groups. The specific objectives of these working groups were to:

- Review the findings of the GSFC workshop with the working groups
- Identify as far as possible the missions (by mode) that will be required to meet the discipline objectives for the period 1978 to 1985
- Identify any new requirements or any modifications to the requirements in the GSFC report for the shuttle and sortie systems
- Identify the systems and subsystems that must be developed to meet the discipline objectives and indicate their priority and/or the sequence in which they should be developed
- Identify any new supporting research and technology activity which needs to be initiated
- Identify any changes in existing procedures or any new policies or procedures which are required in order to exploit the full potential of the shuttle for science, exploration and applications, and provide the easiest and widest possible involvement of competent scientists in space science
- Prepare cost estimates, development schedules and priority ranking for initial two or three missions

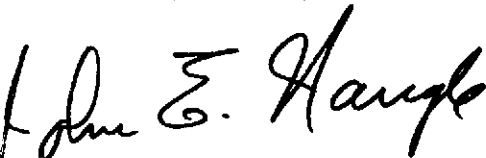
In order to keep this planning activity in phase with the shuttle system planning the initial reports from these groups were scheduled to be made available by the spring of 1973. It was also felt necessary that the individual working group activities be coordinated both between the groups and with the shuttle system planning. As a result, the steering group given in Attachment B was established.

Early in 1973, NASA and the National Academy of Sciences jointly decided that it would be appropriate for a special summer study to review the plans for shuttle utilization in the science disciplines. This summer study has now been scheduled for July 1973. It is anticipated that the results of the working group activities to date will form a significant input into this study.

In the following sections of the summary document are the executive summaries of each of the working group reports. While these give a general picture of the shuttle utilization plan, the specific plan in each discipline area can best be obtained from the full report of that working group. Each working group report has been printed as a separate volume in this publication so that individuals can select those in which they are particularly interested.

From these working group reports it is apparent that an appreciable effort has been made to exploit the full capability of the shuttle. It is, however, also apparent that much work remains to be done. To accomplish this important work, the discipline working groups will continue.

Finally it is evident from these reports that many individuals and groups have devoted appreciable effort to this important planning activity. I would like to express my appreciation for this effort and stress the importance of such activities if we are to realize the full potential of space systems in the 1980s.

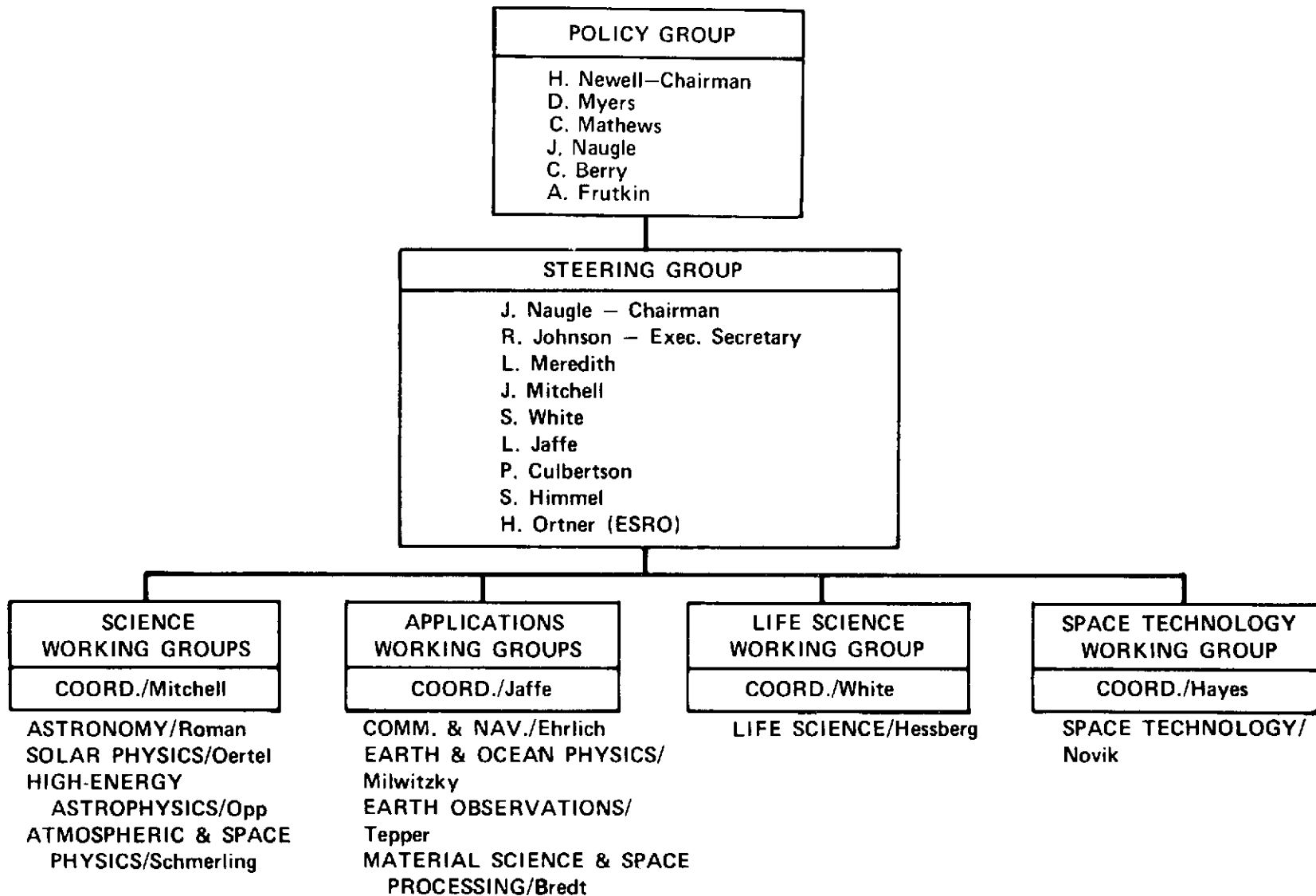
A handwritten signature in dark ink, reading "John E. Naugle". The signature is written in a cursive, flowing style with a large initial "J".

John E. Naugle, Chairman  
NASA Shuttle Payload Planning  
Steering Group

## LIST OF WORKING GROUPS

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2.	ATMOSPHERIC & SPACE PHYSICS	Dr. E. Schmerling (HQ)	Mr. W. Roberts (MSFC)
3.	HIGH ENERGY ASTROPHYSICS	Dr. A. Opp (HQ)	Dr. F. McDonald (GSFC)
4.	LIFE SCIENCES	Dr. R. Hessberg (HQ)	Dr. D. Winter (ARC)
5.	SOLAR PHYSICS	Dr. G. Oertel (HQ)	Mr. K. Frost (GSFC)
6.	COMMUNICATIONS & NAVIGATION	Mr. E. Ehrlich (HQ)	Mr. C. Quantock (MSFC)
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8.	EARTH AND OCEAN PHYSICS	Mr. B. Milwitzky (HQ)	Dr. F. Vonbun (GSFC)
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10.	SPACE TECHNOLOGY	Mr. D. Novik (HQ)	Mr. R. Hook (LaRC)

# NASA AD HOC ORGANIZATION FOR SHUTTLE PAYLOAD PLANNING





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INTERIM REPORT OF THE SHUTTLE SORTIE WORKING GROUP  
ON  
MATERIALS SCIENCE AND SPACE PROCESSING

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MATERIALS PROCESSING AND SPACE MANUFACTURING WORKING GROUP  
EXECUTIVE SUMMARY

The three principal resources that space flight affords for work in materials science and technology are virtual weightlessness, a vacuum sink of unlimited capacity, and energy in the form of solar radiation. Weightlessness is the most important of these resources, since it cannot be duplicated on Earth for more than a few seconds. Prospects for its exploitation include processing of levitated solids and liquids, production and manipulation of mixtures that are not stable in normal gravity, and processes utilizing the enhanced control over heat and mass transfer that is made possible by the convectionless behavior of weightless fluids. Space vacuum and solar radiation are primarily useful as sources of needed utilities, although there is some prospect that wake effects can be used to achieve ultrahigh vacua in large volumes at low orbital altitudes.

The Working Group has identified a wide variety of research and development topics in which space experiments could make useful contributions to metallurgy, semiconductor and electronic materials technology, medical and biological applications, ceramic and glass technology, and fluid physics and chemistry. It is believed that space efforts in these areas can lead to valuable advances in process technology for use on the ground by showing how to control effects due to gravity that cannot be isolated by methods available on Earth. In addition, it is expected that space research and development may lead to manufacturing processes for valuable products that can only be produced in space.

The community that shares interests in the areas of materials science and technology outlined above is worldwide, extremely large and varied, and intimately involved with large-scale industry. Therefore, it is expected that a large user community can be developed for space processing activities very early in the Shuttle/Sortie Lab. flight program, and that user organizations will wish to invest in space research for proprietary purposes as soon as its value has been demonstrated. In order to explore the wide range of potential interests more fully and begin the mobilization of user interest in the exploitation of the Shuttle/Sortie Lab. system, the Working Group strongly recommends that NASA should follow up on its activity by forming a broadly representative advisory group from the scientific and industrial communities to develop comprehensive recommendations for the Space Processing Program.

The Working Group recommends that NASA should plan for a Shuttle Sortie experiment program involving at least 100 investigators in order to give reasonable coverage to the research and development areas identified in its report. It is also recommended that the program should concentrate on making space easily accessible to the international scientific and industrial community and on developing capable research and development techniques in its early phases, with a view to building up a flow of useful results and identifying specific prospects for space manufacturing in a few years. It is anticipated that some promising processes may be ready for reduction to manufacturing practice in space by the middle 1980's.

Because the experiment program must serve a large user community at moderate cost, the Working Group recommends that space processing payloads should be made up from an inventory of general purpose laboratory equipment that the experimenters can use in common. This will necessitate equipment designs that permit individual items of apparatus to be assembled with each other very flexibly to configure payloads for specific groups of experiments, and will also require a continuing program of apparatus maintenance and modification on the ground. For reasons of economy it will be necessary to design apparatus systems for maximum productivity in flight, and it is believed that this will require that operations should be performed under automatic control wherever possible. Heat treating operations seem especially amenable to automation and can probably be performed without direct human intervention in unpressurized payload bay space.

In general, space processing payloads are expected to be constrained by the availability of power and heat rejection capacity rather than size, weight, or crew availability. If the recommended approach to payload design is followed, it should be possible to configure small payloads to fit available resources and carrying capacity on virtually every Shuttle mission. Frequent flights of small payloads would somewhat relax the constraints due to power and heat rejection requirements and would probably be the most efficient way of serving the large and diverse user community that the Working Group envisions. Moreover, sharing of missions with other payloads could obviously help toward the attainment of maximum Shuttle utilization and operating economy. However, it is estimated that the minimum requirements of the recommended program could be approximately satisfied by four dedicated sortie missions per year with payloads that would fit within the foreseeable resources of the Shuttle/Sortie Laboratory system.

REPORT OF THE SHUTTLE SORTIE WORKING GROUP  
ON  
MATERIALS SCIENCE AND SPACE PROCESSING

INTRODUCTION

The NASA Space Processing Program is organized to exploit the capabilities of space vehicles for applied research and development work in materials science and technology, with the specific goals of developing and ultimately commercializing new products to be manufactured in space for use on Earth. Its current projects include studies and research in potentially promising product and process areas; development of techniques and apparatus technology for future flight programs; space experiments on current missions; and planning for intensive utilization of the Space Shuttle and Sortie Lab. The present report gives estimates of the outlook and planning recommendations in the latter area. The report's recommendations regarding worthwhile areas of research and development were prepared with the help of the Working Group's non-NASA members, while the material on Shuttle and Sortie Lab utilization came from NASA sources. However, the entire report has been reviewed by the Working Group as a whole and the text incorporates their comments on all areas.

The topics considered by the Working Group also have an important bearing on the justification for the Space Processing Program, which rests essentially on the appropriateness and feasibility of the program's objectives and the adequacy of its plans for achieving them.

There is little room for uncertainty about the appropriateness of what the program seeks to accomplish. Since successful commercialization of space products will necessarily imply an economic return exceeding production and distribution costs, commercially viable space manufacturing operations will be justified, if successfully instituted, by the same considerations that apply to other forms of productive economic activity. Applied research that increases the effectiveness or productivity of technology used on the ground is economically productive in the same sense. In addition, the development of means to apply space flight to the production of profitable goods and services is clearly within the mission defined for NASA by the National Aeronautics and Space Act. However, the Working Group has not concerned itself with the economic justification and feasibility of the Space Processing Program's research and development objectives.

In any case, estimates of the feasibility of the program's objectives are at best somewhat conjectural at this early stage of development. The adequacy of

these estimates, as well as that of the program's implementation plans, should be a subject for continuing critical review, and the Working Group hopes that its report will provide a proper basis for the informed criticism that such reviews should entail. The group also believes that the Space Processing Program can benefit considerably if its plans and progress are reviewed and discussed by groups representing the broadest possible cross-sections of the scientific and industrial communities, and recommends that steps should be taken to bring this about.

The report opens with a summary description of the potential offered by spacecraft for work in the materials sciences and technology and a statement of the Working Group's views on worthwhile areas of research and development for the program to pursue. The group believes that these sections give a reasonably complete overview of current status in the program's technical areas, but wishes to emphasize that its membership was too limited to attempt a really comprehensive consideration of what space has to offer for the development of new knowledge and novel applications of materials. Moreover, within the limits of time and resources available to it, the Group has not found it possible to criticize in depth the probability of success for any of the areas considered. It is hoped, however, that the material presented will furnish a suggestive basis for further thinking when it is reviewed by more widely representative groups.

The two opening sections are followed by a discussion of the Space Processing Program's general plans for conducting research and development activities designed to lead to space manufacturing applications; a statement of the program's specific objectives for the first ten years of Space Shuttle and Sortie Lab operations; and a brief narrative description of its plans to achieve these objectives. The program's sponsoring office concurs with the Working Group in wishing for wide awareness and discussion of its plans among scientists and industrial managers, and for criticisms of their adequacy as well as suggestions for their improvement.

Finally, the report concludes with detailed discussions of the modes of Shuttle and Sortie Lab utilization foreseen for the Space Processing Program, the requirements imposed by these utilization modes on missions and vehicle systems, and recommendations regarding Shuttle/Sortie Lab utilization policies and development actions that would facilitate the program's work. Technical information on some specimen payloads is included in a group of appendices.



## USES OF SPACE IN MATERIALS SCIENCE AND TECHNOLOGY

### UNDERLYING CONCEPTS

Space flight affords three principal resources that may prove valuable for future work in materials science and technology:

- The condition of virtual weightlessness obtained in spacecraft during drifting flight.
- The infinite vacuum sink provided by space.
- Unattenuated solar radiation

However, since the recurring costs of going into space will run to millions of dollars per flight with any foreseeable transportation system, flights are likely to be made only for the sake of advantages that cannot be obtained on Earth at comparable costs. Extended weightlessness is the item in the above list that most obviously meets this condition, and therefore the discussion in this report is focused on processes that depend on weightlessness. However, the properties of the space vacuum and solar radiation can only be approximated on Earth, and their exploitation in space does seem to offer a few potential features that would be difficult or impossible to duplicate under the Earth's atmosphere. These are discussed below, and in the present state of the subject it seems best to reserve judgement as to their value and uniqueness. In addition, it is very likely that many experiments and processes essentially based on weightlessness will use the space vacuum and solar radiation as sources of needed utilities.

### WEIGHTLESSNESS

The condition found in a spacecraft drifting with no propulsion is actually one of free fall modified by low-level accelerations due to drag effects, orbital dynamics, and the operations of the vehicle's systems and crew.

The technical exploitation of weightlessness is a demanding and unusual undertaking, because it challenges one to surrender or profoundly modify many habits of thought ingrained by lifelong conditioning in the earth's  $980 \text{ cm/sec}^2$  acceleration field. For example, in a freely flying spacecraft bubbles and bullets will drift equally well through the air, though with different momenta. Fluid heat transfer tends to be dominated by conduction rather than convection, small forces can produce more clear-cut effects because they are not masked by

gravity effects, and there is no preferred vertical direction. These and other unfamiliar conditions require some basic shifts of viewpoint that are not easy to practice consistently, and creative thought about their exploitation is apt to be stifled by the effort of adjustment or stultified by the overoptimistic assumption that surprising and valuable things are bound to happen spontaneously under such novel conditions.

In all probability, however, any new processes or valuable modifications of familiar ones that may be possible in space will be achieved only because they are deliberately engineered. Because of this, concepts for applied research and manufacturing applications of space flight are unlikely to mature fully until many materials scientists and engineers have gained direct experience in space research and development work and have accumulated a fund of information on how physical and chemical processes actually behave in space. We therefore expect that most of the significant developments in space processing will occur after the Space Shuttle and Sortie Lab have begun to provide capabilities that allow research and development to be practiced in space in a manner and on a scale approximating what is possible in ordinary laboratories on the ground.

On the other hand, the study work and preliminary space experiments already accomplished have provided a reasonably clear view of the main lines along which future concepts are likely to develop. Generally, we expect these concepts to emphasize new methods of control over processes and experimental conditions which are made possible by weightlessness. The types of process control that seem potentially available and some of their prospective uses are summarized below.

### Levitation Processes

The possibility of levitating solid objects and liquid masses is probably the most familiar prospective advantage of weightlessness, and processing of levitated materials without containers or other physical contacts should make it possible to control contamination and other disturbances due to contact with foreign materials. This possibility might be exploited by processes for the ultra-purification of materials by floating zone refining of levitated ingots or by evaporation of relatively volatile impurities from refractory materials.<sup>1\*</sup> Levitation techniques are available on Earth for some applications involving metals, but not for non-conducting materials. In addition, as W. G. Pfann suggested in 1958,<sup>2</sup> weightlessness can be expected to remove some of the constraints that limit the dimensions of molten zones that can be maintained in any given material in the floating zone method of crystal growth and material purification.

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\*See List of References

Another possible levitation process may be the preparation of new types of optical glass by cooling molten oxides into the glassy state without external disturbances that can nucleate unwanted crystalline grain growth.<sup>3,4</sup> Similarly, levitated samples of molten metals and alloys may be convenient subjects for experiments involving supercooling and homogeneous nucleation; the absence of container walls will eliminate one source of unwanted nucleation sites, although other nucleating sites may be present in the sample materials themselves.

A final example, closely related to actual manufacturing processes, is that of growing semiconductor or optical crystals from a levitated melt that is shaped by external fields to produce the crystals in forms such as ribbons or sheets that have the dimensions required for final use.<sup>5</sup> In this way it may be possible to produce semiconductor device materials or optical components such as windows and mirrors whose perfection need not be compromised by subsequent cutting, grinding, and polishing operations.

All of the above processes require non-contacting means of manipulating levitated objects and of stabilizing their positions against spacecraft accelerations and the relative velocities that arise when the objects are not at the vehicle's center of mass. On the other hand, levitation processes are not generally expected to be sensitive to the low accelerations that these operations will involve. The Space Processing Program is currently sponsoring development of levitation control systems based on electromagnetic forces<sup>6</sup> and acoustic pressure.<sup>7</sup> Some preliminary experience with the solidification of levitated molten metals will be provided by Skylab experiment M553, Sphere Forming.

#### Mixture Stability in Space

A second source of process control, somewhat analogous to applications of levitation, is found in the lack of buoyancy in weightless fluids. Since nothing will float or sink in a truly weightless liquid, it may be possible to position fibers and particles precisely in molten metals and freeze them in place to produce high-performance composite materials. A simple version of this technique will be tested by the Japanese National Research Institute for Metals in Skylab experiment M561, Whisker-Reinforced Composites. It has also been suggested that controlled arrays of gas bubbles might be introduced into melts to produce "metal-gas composites" or cast components that contain metal only where it is needed for strength.<sup>8</sup> Some preliminary data on the stability of molten metal structures containing large fractions of distributed void volume will be obtained from Skylab experiment M565, Silver Grids Melted in Space, by the Katholieke Universiteit Leuven.

In metallurgical research, the lack of segregation due to density differences between phases may aid studies of a variety of questions. For example, it has

been suggested that space experiments could provide new insight into liquid-liquid segregation in monotectic alloy systems, and that solidification of such alloys in the two-melt composition range could produce some novel microstructures.<sup>9</sup> This possibility is being tested on a small scale in tests in the MSFC drop tower facility<sup>10</sup> and will be investigated further in Skylab experiment M557, Immiscible Material Compositions, by the TRW Systems Group.

The free-fall stability of mixtures that are inherently unstable on Earth is also likely to find applications in physical methods of chemical separation. One such that is currently under development by the Space Processing Program is the separation of living cells and other particles that are significantly denser than water by electrophoresis in liquid media.<sup>11, 12, 13</sup> Two simple tests of this concept have been performed on the Apollo 14 and 16 lunar missions,<sup>14, 15</sup> and the results have been such as to encourage further development work.

In general, processes that depend on freedom from buoyant forces are expected to be more sensitive to spacecraft acceleration levels than levitation processes, particularly where they involve mechanically unstable structures such as melts containing voids. In addition, processes in this class tend to involve relatively detailed manipulation of material structures, and their reduction to practice is likely to require a quite extensive series of engineering experiments in space.

#### Control Over Heat and Mass Transport in Fluids

An important potential source of process control based on weightlessness is the elimination of convection in fluids due to buoyancy forces, with only insignificant disturbances from spacecraft accelerations. Under such circumstances, heat and mass transport in liquids and gases should be governed solely by diffusion, heat conduction and radiation without the great complications of fluid flow. Thus, new sets of experimental conditions should be available in space, and both apparatus and experiment design may be simplified for a wide variety of circumstances.

It should be noted that certain second-order fluid flow effects, usually masked by gravity-driven convection, may result from temperatures and concentration gradients which introduce point-to-point variations in surface tension and thus surface tractions;<sup>16, 17</sup> considerable amounts of engineering work may be needed to eliminate or control these.<sup>18</sup> It should also be noted that freedom from buoyancy driven convection is achieved on earth in certain special arrangements, such as in liquids heated from above and in magnetic damping of conducting fluids. Nevertheless the prospect presents itself that for the first time a very

wide range of physical and chemical processes, including heterogeneous material systems with liquid and vapor phases, may come under a much higher degree of control and prediction.

This type of process control has potential applications in many types of solidification and crystal growth techniques, and its possibilities account for much of the interest which materials scientists have displayed in the Space Processing Program to date. In fact, 9 of the 15 Skylab experiments sponsored by the program are designed to investigate such processes. For example, weightlessness is expected to make a wide range of idealized transport and temperature conditions available for crystal growth from vapor media. It may also be possible to grow highly perfect crystals from aqueous and other solutions on unsupported seeds by diffusion-controlled transport.

Space techniques for all types of controlled solidification and crystal growth are likely to differ markedly from the techniques that are now used on earth. For example, the well-known Czochralski growth technique of crystal "pulling" from the melt would in space involve the absence of thermal convection, probably the absence of the usual melt container, and perhaps a different meniscus effect from that encountered on earth. It appears quite possible that novel techniques which take full advantage of weightlessness may be capable of overcoming problems such as impurity banding which lowers the yield of some types of electronic devices on silicon chip surfaces, and may also provide better yields of crystals that are difficult to grow on earth.

Control over heat and mass transport in weightless melts has also been suggested as a means of producing controlled structures in eutectic alloys<sup>19</sup> and making specialized optical components free from performance-limiting defects.<sup>20</sup> Several preliminary trials of weightless solidification effects were conducted in simple apparatus on the Apollo 14 lunar mission.<sup>21</sup>

The value of weightlessness in stabilizing mixtures to be separated by electrophoresis in liquid media has been mentioned above; in the actual separation process, the stability of the liquid separation medium itself will be of equal or greater importance. On earth, electrophoresis and its derivative techniques, such as isotachophoresis and isoelectric focusing, are successful only in arrangements where the separation medium is stabilized against convection and other mechanical disturbances either by containment in a porous supporting medium or by a stable flow regime. In space flight, on the other hand, this requirement is considerably relaxed because only small accelerations are present.

Consequently, it is conceivable that powerful new electrophoretic separation methods could be developed to operate in space. Such methods might possibly

be capable of yielding immediate benefits in medical and biological research applications such as the production of pure preparations of living cells. Ultimately, they might also provide means for large-scale production of products for therapeutic and preventive medicine.

Following the relatively encouraging small-scale electrophoresis tests performed on Apollo 14 and 16, the Space Processing Program initiated a project to add a large preparative separation system to the Skylab payload. A practical system was designed and fairly extensive "breadboard" development work was accomplished,<sup>22</sup> but scheduling and funding problems forced the abandonment of the attempt before work was begun on apparatus for use in flight.

Finally, since heat and mass transport are controlling factors in all chemical processes, we may expect a rather wide field to develop for space applications in chemistry and biochemistry. In the short run the ability to perform experiments involving controllable distributions of temperature and concentration in quiescent fluids will probably be most immediately beneficial as a research technique in physical chemistry. On the other hand, the possible biochemical applications seem the most exciting over the longer run. One interesting speculative possibility in this area is that of bringing incubation processes used to make biological preparations under reliable control. At present, control over such processes tends to be somewhat marginal because exact manipulation of a growing microorganism's chemical environment is often very difficult. Space flight may make such manipulations possible, and it may well be found that some important biological products of the future will depend on production methods that can only be controlled well enough to give predictable results in space.

From this extended discussion, it will be evident that processes involving control over fluid heat and mass transport can be highly sensitive to acceleration levels. Some may have to be isolated from spacecraft "noise" by levitating relatively large apparatus systems in the Sortie Lab, just as experiment packages for sensitive tests are allowed to drift freely in present-day "zero-g" aircraft flights. In extreme cases, such as very slow crystal growth from solutions, it may even be necessary to resort to operations with small free-flying satellites.

It is also clear that the refined and subtle methods of control to be utilized in this class of processes will require considerable amounts of sophisticated development effort. However, the potential for novel results and unique product innovations seems good in this area, and we believe that it should be vigorously pursued.

## SPACE VACUUM

At the orbital altitudes that will be normal for Space Shuttle operations, the number density of ambient gas molecules corresponds to a pressure of  $10^{-8}$  to  $10^{-9}$  Torr., which is well within the range achievable on the ground by commercial high vacuum apparatus. In addition, the region near the Shuttle will contain appreciable concentrations of molecules originating from the vehicle itself, even when rigid contamination control measures are in effect.

By itself, therefore, the space vacuum cannot be regarded as a unique advantage for the kinds of work contemplated by the Space Processing Program. For ordinary purposes, we believe that vacuum processes on the Shuttle missions will be implemented most conveniently in accessible vacuum systems carried inside the vehicle. However, the external vacuum will provide an extremely convenient "pump" for such systems, characterized by high capacity and cleanliness at all pressures down to the ambient level.

On the other hand, it has been suggested<sup>23, 24</sup> that the flight characteristics of the Shuttle or other orbital vehicles might be exploited to provide pressures much lower than ambient, and perhaps lower than any earth-based apparatus can attain. Since orbital velocities are of the same order of magnitude as the thermal velocities of gas molecules in space, an orbiting vehicle sweeps away the gas in its path and the number density directly behind it is reduced to what is available from the part of the velocity distribution that has relatively large components normal to the orbital path.

Contamination problems would probably prevent one from gaining much by deploying experiments in the unmodified wake of the Shuttle itself, but with properly designed and located shielding devices it seems possible that very clean ultrahigh vacuum conditions might be obtained. Since such a vacuum facility would have only one "wall," problems associated with back reflection of gases evolved from samples in the vacuum space could also be largely avoided.

## SOLAR RADIATION

Many of the possible processes discussed above would require considerable amounts of heat energy at high temperatures, and even the small-scale experiments envisioned for the early phases of the program's Shuttle mission activities will probably suffer some restrictions due to the limited electric power resources expected to be available on the Shuttle and Sortie Lab. The energy available from unattenuated solar radiation in space therefore has some definite attractions, especially since it is easily converted into heat. Solar concentrators can

provide about one thermal kilowatt per square meter of area, so that devices of rather modest size could significantly increase the Shuttle system's capacity to support high temperature experiments. Moreover, radiation is intrinsically a very clean source of heat and might constitute the only practical means of producing high temperature in ultrahigh vacuum facilities of the sort suggested in the preceding section.

However, the exploitation of solar heat in space involves some considerable practical engineering problems. At ordinary inclinations radiation is available for only half of each 90-minute orbital period, and it can only be obtained for long periods in high inclination orbits where payloads are reduced and operating costs are correspondingly increased. In any orbit, a solar concentrator would require a pointing system that could hold its orientation more or less independently of the Shuttle's attitude, and pointing accuracy requirements might be rather severe if the system had to maintain precisely controlled constant temperatures. Solar heat also would not be easy to use inside the pressurized Sortie Lab where samples and apparatus would be easily accessible, and if it were brought into the vehicle in significant quantities means would have to be provided to remove it as well. On the other hand, some rather complicated remote manipulations would probably be needed to make effective use of a concentrator outside the pressurized space.

Because of these difficulties it is not obvious that solar heating has any advantages over auxiliary electric power sources for experiments in the early years of Shuttle operations, and we recommend that very detailed engineering trade studies should be conducted before any concrete plans are made to develop solar concentrators for the Space Processing Program. It seems quite likely that the tradeoffs will be found favorable to solar heating only at thermal power levels of the order of tens of kilowatts, where the radiator and fuel cell tankage requirements for electrical heating inside the spacecraft would begin to impinge severely on Shuttle system constraints.

## RECOMMENDED AREAS FOR RESEARCH AND DEVELOPMENT

In recommending areas of research and development where useful space processing applications seem likely, the Working Group has two objects in view. The first is to furnish an approximate estimate, as requested by NASA, of the probable scientific and technical content of the Space Processing experiment program to be implemented on the Shuttle Sortie missions. The second, and in our view equally important, object is to provide a starting point for discussion of the potential for space processing among scientists and engineers who have not hitherto come into contact with the program.



## RESEARCH AND DEVELOPMENT AREAS

For the purposes of this report we have found it convenient to divide the subject matter of space processing into four areas representing the interests of approximately equal parts of the portion of the user community with which the program is already in contact. It seems most appropriate to classify these areas according to the materials in which different groups of users are interested, since this involves the least overlap between divisions. The areas selected for discussion are as follows:

1. **Metallurgical Processes:** This area comprises all applications based on the normal properties of metals and metallic alloys, including metal-matrix composite materials.
2. **Electronic Materials:** In this category are grouped applications that depend on interactions between electrons in materials and externally applied influences such as electromagnetic fields, mechanical forces, etc.
3. **Biological Applications:** This area includes all applications involving materials of biological origin.
4. **Non-Metallic Materials and Processes:** This area comprises essentially all of the applications that are not specified under the three preceding areas, including glass and ceramic technology, chemistry, and physical processes in fluids. We expect that it will become necessary to divide this category into several independent areas when user interests develop further.

### Metallurgical Processes

The Working Group has identified four major types of metallurgical processes in which weightlessness and other features of space flight may prove to be important for applied research or for eventual manufacturing applications:

Solidification—Among solidification processes we include the preparation of metal single crystals, polycrystalline castings, and polyphase alloys.

It is expected that techniques for growing highly perfect single crystals of metals in space will develop along much the same lines as those for semiconductors, and that space research can help to clarify the effects of container walls and convection on crystal perfection and impurity distributions. If crystals of very

high perfection can be produced they are likely to find many uses in research on the fundamental mechanical, electronic, magnetic, and other properties of metals on the ground.

It should be noted that weightlessness should relieve some serious problems encountered on earth in handling easily deformed crystals of soft metals such as copper, gold, aluminum, etc. This may make it desirable to carry out some steps of specimen processing and evaluation in space. It will also be necessary to provide relatively sophisticated special means of packing metal crystal samples for return to Earth so that they cannot be deformed by reentry and landing acceleration loads.

Research on weightless solidification processes that produce polycrystalline metal castings can develop new information on how convection and container wall effects influence the grain structure of the product. Such research may also have some value in clarifying the kinetics of segregation effects in alloys that do not melt and freeze congruently. It also appears possible that studies of supercooling effects in containerless melts can lead to new results on the kinetics of nucleation and on methods of grain refinement. Data from space experiments on polycrystalline solidification are expected to find some direct applications in resolving problems associated with solidification processes used on the ground.

The most promising areas for space work on solidification of polyphase alloys seem to be those connected with eutectics and alloy systems that have liquid miscibility gaps. It is well known that eutectic alloys can be solidified under controlled conditions to produce highly oriented lamellar structures which have considerable promise for applications requiring high strength at elevated temperatures and some prospects for more speculative uses in sophisticated optical and electronic devices. It is expected that work on controlled solidification process in space can lead to improved methods that could give more perfect structures with enhanced properties, and perhaps also somewhat better control of lamellar spacing and other structural parameters.

For alloy systems with miscibility gaps, space affords an opportunity to study liquid-liquid segregation and solidification in the composition range corresponding to liquid immiscibility, without buoyant segregation of the heavier from the lighter components. Samples prepared in this way and studied on the ground can provide new information on phase stability, electronic properties, and other characteristics of such alloy systems. In addition, it may be found possible to produce metastable homogeneous or finely dispersed alloy compositions with desirable electrical or magnetic properties by rapid cooling through the temperature range where segregation can occur.

Purification—Two specific cases have been identified in which the characteristics of space flight can be used to improve techniques for the ultrapurification of metals.

One case is that of floating zone refining; weightlessness will remove the constraints imposed on floating molten zones by the weight of the liquid, and this should make it possible to process materials that are intractable to methods available on Earth. In addition, it may be possible to gain some significant advantages from refinements of control over heat and mass transport in the melt.

The other purification method for which we foresee advantages is that of evaporating relatively volatile impurities from a liquid or solid sample. In space this method can be applied to levitated samples so that contamination from containers can be eliminated. Also, the technique discussed above for producing high vacua behind shielding devices may provide better protection against gaseous contaminants than can be obtained on Earth.

Composite Material Preparation—We believe that the important research and development topics in this area will concern the production of controlled dispersions of fibers, particles and voids in liquid metal matrices with subsequent freezing to produce high performance composites, and the preparation of composites from solid materials by bonding processes whose effectiveness may be enhanced by the ultraclean high vacuum conditions that may be obtainable.

Specimen Preparation—One of the most effective services that the Shuttle/Sortie Lab system may be able to perform for metallurgical science is that of preparing metal specimens in otherwise unobtainable forms for research use on Earth. Crystal growth and ultrapurification will obviously be of value in this respect, but the simple ability to melt significant amounts of metals without the use of containers may be equally important. We therefore recommend that strong emphasis should be given to containerless melting methods and to interactions between levitated melts and the positioning systems that maintain them in the planning and engineering of payloads for the Shuttle and Sortie Lab.

### Electronic Materials

The class of electronic materials as defined above represents a very important and potentially productive field of research and development for the Space

Processing Program for two reasons:

- Such materials are commonly used in high-technology products where the value added by manufacturing processes is frequently high, and
- The performance of these materials in applications depends sensitively on the quality of their preparation which in many cases involves processes that can be affected by gravity.

Electronic materials that are likely to be of interest to scientific and industrial users of the Space Shuttle and Sortie Lab include the following:

- Conventional Semiconductors used to make active circuit elements such as diodes, transistors, integrated circuits, light-emitting diodes, photovoltaic cells, etc. These materials include a variety of chemical compounds as well as elemental silicon and germanium.
- Electro-Optical Materials used for processing optical signals and in the implementation of electronic functions by optical means. Conventional semiconductors are used for some of these applications, but new technology is developing toward use of insulating crystals such as triglycine sulfate and oxide-based materials such as lithium niobate, lead germanate, bismuth titanate, etc.
- Magnetic Domain Materials, for which the most interesting current application prospects are in information storage, as in "magnetic bubble" computer memories. Materials in this class are generally complex oxides such as ferrites and rare earth/iron garnets.
- Laser Materials, including optical harmonic generators. Solid state lasers are either of the injection diode type that uses compound semiconducting materials or the optically pumped type based on doped glasses or oxide-type crystals that must be of high optical quality. The latter requirements are also necessary in harmonic generators for which the most familiar materials are potassium dihydrogen phosphate and lithium iodate.
- Superconductors, whose primary applications are in high-field magnets, but which have many important potential applications that may be realized if materials can be found that can be operated with coolants other than liquid helium. The first known superconductors were pure metals, but the current trend of development is toward complex intermetallic compounds and heterogeneous materials with precisely controlled internal structures.

- Piezoelectric Materials, which function as transducers between mechanical and electrical energy in ultrasonic generators, electronic delay lines and filters, and surface wave devices, as well as in more familiar devices such as microphones and phonograph pickups. Quartz is the most commonly used material now, and advanced materials include oxide-type compositions such as lithium niobate, bismuth germanate, and lithium tantalate.

All of the applications mentioned above are based on the fundamental properties of the materials in question, and thus it is necessary both for applications and for research purposes to obtain these materials in forms that manifest the properties of interest most clearly. In all cases the required forms of these materials are produced through solidification, either by synthesis or by conversion of one solid form into another through an intermediate process of melting, vaporization, or dissolution in a solvent. Except for laser glasses and superconducting wire, the desired end product is a single crystal of some appropriate configuration. However, requirements on single crystals as well as on other forms of electronic materials may vary widely according to the type of application that motivates interest in the material.

Therefore, practically all kinds of solidification effects will be of interest in space research on electronic materials, and the need for precise control over the structure and constitution of the product will be virtually the only unifying theme. Almost all processes of interest in this field will involve temperature changes, so that thermal effects in the materials being prepared and in the intermediate phases that precede them will be of great importance. Thorough understanding and precise control of heat transfer and thermal gradients will be required in all of these processes, and experimental studies of diffusion and convection effects will be needed to reduce any process to consistent, controllable practice.

In general, surface and interface behavior will be critical in all preparation processes where the product is in contact with one or more intermediate phases. Nucleation and growth kinetics will control the production of the product as well as unwanted adventitious crystals in crystal growth from vapors and solutions while in growth from melts the stability of the solidifying interface will be an important concern. Strict control will be needed over the stoichiometry of chemical compounds in this class of materials, and effects that tend to segregate components within the solid or between the solid and intermediate phases involved in the preparation process will call for intensive research and process development work in space. Segregation effects are an unqualified hindrance to the production of uniformly doped conventional semiconductors, but there is some evidence that growth bands are necessary for the

proper functioning of "magnetic bubble" materials, and segregation may offer a possible avenue toward preparation of superconducting heterogeneous layered structures. Since control over the internal structures of materials will also be a common theme in this field, mechanisms of defect production during solidification will be an important research topic as well.

Purification of electronic materials is not regarded as an outstanding problem for space research since methods already established on the ground are adequate for semiconductors and for materials that may be used in synthesis of electronic materials. On the other hand, it will be necessary to avoid contamination by crucibles and other foreign materials in many processes, and especially in the preparation of laser glasses for high-power applications and in high-temperature solution crystal growth from corrosive solvents. Because of this, we anticipate that the program will require means of confining and manipulating levitated melts of both conducting and non-conducting materials.

In conclusion, although we foresee that most work on electronic materials in space will be connected with preparation processes, it must be realized that equivalent amounts of effort will also be required on the ground to characterize the materials prepared in space experiments. If the space work succeeds in producing materials in previously unavailable forms, in all probability new characterization methods or extensions of existing methods will be needed to verify and build upon this success. Therefore, we believe that the Shuttle experiment program will make it necessary for both user organizations and the Space Processing Program to undertake significant amounts of ground-based research and development work on refined methods for studying the properties of electronic materials.

### Biological Applications

Materials of biological origin are not ordinarily regarded as part of the subject matter of materials science and technology. However, physical and chemical techniques derived from the traditional materials sciences have played an increasing role in the biological sciences over the past two decades, and it seems probable that the employment of such techniques in research may eventually lead to their adaptation to production processes as well.

Therefore, over the time span one must visualize for the development of space manufacturing operations, the relationship between biological applications and the rest of the Space Processing Program may come to be much closer than surface appearances would indicate at present. Moreover, the prospects for economically viable space manufacturing operations appear relatively good in this field, because of the high added value associated with preparations needed

in therapeutic and preventive medicine and also because of the social and indirect economic benefits that result from reductions in the incidence of disease and disabling conditions.

In discussing biological and medical problem areas that might benefit from space processing capabilities, the Working Group has found it appropriate to divide the biological applications area between interests in the properties of biological materials and in development of new or refined methods for processing such materials. These two fields of interest are sharply distinguished in subject matter, and at least initially their commonality with other space processing areas will tend to be concentrated in the field of methods. On the other hand, scientists working on materials naturally tend to become involved in developing preparation methods, and work on processing techniques involves materials properties in essential ways because such work is generally motivated by materials problems. Thus neither field will or can be pursued in isolation, and both must be represented in the Shuttle experiment program.

The biological methods of greatest initial importance appear to be those connected with separation and purification of biological materials. Such methods generally involve manipulations of material suspended in liquids analogous to body fluids, since the materials in question tend to be unstable in chemical environments that differ radically from their natural ones. It appears that the increased latitude available for fluid manipulations under weightless conditions in space may make significant improvements in separation and purification methods possible.

There are some significant needs for such improvements. From the molecular to the cellular level, materials produced by life processes generally occur as mixtures of components that are similar in their gross properties but differ in their fine structure in ways that decisively affect their biological functions. Much current medical and biological research is concerned with distinguishing among the components of mixed materials such as immunoglobulins, similar cell types, etc., and identifying their different functions. If successful, space separation techniques offering capabilities not available on the ground would find immediate applications in support of this research. It also seems likely that the interplay between research progress and continuing technique development can lead naturally to space production processes for any resulting medical or other products.

The separation processes of most immediate interest for research and development in space are electrophoresis, isoelectric focusing, and isotachophoresis, all of which are based on electrical transport of organic molecules and particles in liquid media. Each of these techniques is used in several variant forms, but in all of them the range of usable process parameters and equipment designs is

restricted on Earth by gravity-driven disturbing effects, especially thermal convection and sample sedimentation. The wider range of process conditions accessible in the low acceleration environment afforded by the Shuttle/Sortie Lab system should make it possible to develop new and improved forms of electrical separation processes which may be useful both for analytical purposes and for the preparation of usable quantities of material for research and applications.

Since there are many possible forms of these processes, each having advantages for certain applications, we believe that research involving them may prove to be one of the most active single areas in the space processing experiment program. To support this effort it will also be necessary to develop a considerable range of complementary techniques for the handling and preservation of biological materials in space. Included among these needed procedures will be centrifugation, dialysis, cryogenic freezing and lyophilization, as well as general laboratory techniques for making and handling precisely standardized chemical solutions, cleaning and sterilizing apparatus, etc. For some especially sensitive materials it may also be necessary to provide means of performing evaluation tests on samples promptly after they are prepared.

It will probably be possible to develop other biological methods whose use in space can be valuable as well. For example, refined methods of crystal growth from solutions under diffusion-controlled conditions may be capable of providing high-quality crystals of protein-based materials such as DNA, enzymes, etc., for precise structure determinations. Another intriguing idea is that of preparing pure materials by fractional precipitation, since precipitates in solutions would tend to remain localized where they were formed. Precipitated proteinaceous materials could be held in suspension at their isoelectric points in an isoelectric focusing column, for instance, or perhaps cryoprecipitates could be fractionated by preparation in a temperature gradient.

A final speculative example is that of what might be called "aerosol microbiology." Cultures of cells or microorganisms might be maintained in suspensions of weightless liquid droplets exposed to a gaseous environment containing nutrients as well as an appropriate atmosphere, so that all of the cells would experience precisely similar ambient conditions. Such an arrangement might offer significant advantages in controlling incubation processes, and might also realize considerable conveniences in harvesting the cells and/or their metabolic products in uncontaminated forms.

Biological materials are virtually infinite in variety, and we can do no more than suggest examples of the research areas that may motivate development of biological methods in space and employ them if they are successful.



Undoubtedly medical research and applications will provide the most important uses of space techniques. As noted above, there is a continuing and probably permanent need for pure preparations of research materials, and considerable refinements of technique are needed to separate subtly different varieties of substances such as antibodies, enzymes, hormones, lipoproteins, and other products of physiological processes according to their functions and effects. Similar and in many cases complementary needs exist for highly purified preparations of antigens, enzyme substrates, and products of pathological conditions for use as analytical reagents and for development or application of diagnostic tests. Requirements of the above types are so varied and numerous that considerable interest and extensive usage seem assured for any space preparation method that offers new capabilities.

In addition to pure biochemicals, some areas of medical research have significant needs for preparations of pure strains of living cells, and these are likely to expand greatly as research progresses. In the short run refined cell separation methods would probably find their most extensive uses in effort to identify differentiating factors among cells of a given type (such as lymphocytes, normal and malignant cells from the same organ, etc.) and determine their functions. As work of this type proceeds it may generate needs for the maintenance of pure cell strains in culture, and therefore for continuing preparative separations to provide fresh culture material. In the longer run, rather large numbers of cell separations may be needed for therapeutic uses such as transplants. For example, some encouraging experimental successes have been registered in restoring the bone marrow of irradiated mice by transplantation of electrophoretically purified stem cells. It is likely that human patients would be much more sensitive to the purity of the transplanted cell fraction, and if space preparation proves to be necessary to solve this problem it is certain to find extensive employment.

Although the above discussion is focused on applications to human medicine, it will be obvious that many of the same interests exist in other branches of biology and could be served by similar means. One example that seems specially relevant is that of cell separation methods, which could be valuable in supplying pure strains of microorganisms for culture maintenance and research purposes. In addition there would be considerable interest in space-based incubation and culturing techniques if they could provide products that were not otherwise available.

### Non-Metallic Materials and Processes

As its name implies, this area combines a set of somewhat miscellaneous interests that do not fit smoothly into the other areas and have smaller

constituencies in the scientific and industrial community. Taken as a whole, however, this combination of interests may generate a total level of activity equivalent to that in any of the major areas described above.

Glass and Ceramics—Prospects for space activity in glass technology include the production of new types of glass, processing methods to improve the quality of conventional glasses, and the manufacture of glass products.

The idea of producing new types of glass is based on the possibility of solidifying levitated, containerless melts of metallic oxides or analogous materials rapidly and without exposure to external influences that can nucleate unwanted crystalline grains. It has already been verified in laboratory experiments that small beads of some oxides can be cooled into glassy states in free fall, thus producing materials with previously unobtainable optical properties. The long-duration weightlessness available in space flight will make a much wider range of containerless processing variables possible, so that investigators can systematically survey potential glass-forming materials and perhaps develop means of preparing samples sufficiently large and homogeneous for optical applications.

Potential glass processing operations using conventional compositions are centered on containerless processing to eliminate sources of contamination and on the expected lack of stratification in weightless melts composed of ingredients of differing densities. These combined effects should make it possible to produce glass of very high purity and optical homogeneity, which could find applications in high-resolution optics, high-power laser systems and low-loss fiber optical transmission lines.

Work on both new and conventional glass compositions will require capabilities for heat treating levitated solid and molten insulating materials under precise temperature control and with protective atmospheres whose compositions can be adjusted over the range necessary to maintain compositional stability in the materials treated. In addition, attempts at producing new glasses will need means of cooling levitated melts at rapid, controllable rates.

Novel methods of preparing glass products should also be possible at low acceleration levels. For example, Dr. Emil Deeg of the American Optical Company has suggested that glass bodies of high surface perfection might be produced by forming and fire polishing them while levitated, and that solid Christiansen filters could be produced by weightless melting. A Christiansen filter is a dispersion of small transparent particles in a transparent matrix, made with materials selected so that their refractive indices match at only one wavelength;

light of this wavelength is transmitted without loss, while all other wavelengths are strongly scattered by multiple reflections. In addition, there might be some advantages in drawing very fine and very long optical fibers in weightlessness. It seems likely that many other possible operations will be invented as engineers gain enough familiarity with weightless manipulations to exercise their ingenuity on them.

Ideas for producing ceramics in space have received less attention than glass technology and are less well developed. However, we believe that systematic investigation will reveal a considerable potential in this area as well. One obvious possible application would be the synthesis and growth of precisely controlled and perhaps novel ceramic compositions by chemical vapor transport under convectionless conditions. Another, which is more speculative because of its high temperature requirements, is the production of two-phase ceramic composites with controlled internal structures by controlled eutectic solidification; for example, using the  $\text{ZrO}_2\text{-Al}_2\text{O}_3$  eutectic. As a final suggestion, it may be possible to apply the vaporization purification technique described above for refractory metals in the case of ceramics as well.

Physical Chemistry—If weightlessness makes it possible to realize experimental conditions in which heat and mass transport in liquids and gases can be made to behave in predictable ways determined by initial and boundary conditions under the control of the experimenter, a wide field will be opened for studies of the physical chemistry of heterogeneous systems, and perhaps also for applications.

In polymer chemistry, for example, it should be possible to study topics such as chain propagation and catalytic polymerization under nearly ideal conditions. In addition there appears to be a potential for work that would shed new light on polymer crystallization.

More generally, since any heterogeneous system can potentially be maintained in a finely dispersed homogeneous form in space, it should be possible to perform extremely detailed studies of reaction kinetics. By delineating the fine structure of such features as activation energy spectra, such studies could lead to new understanding of technically important chemical processes, and possibly to new process control methods or other applications.

Physical Processes in Fluids—The same features of space flight that are of potential value for physical chemistry should also have applications to studies of fluid behavior. As a simple example, space should be an ideal setting for precise studies of diffusion and thermal conduction in gases and liquids, and such studies may reveal new knowledge about the detailed mechanics of molecular motions in much the same way as similar work has done for solids.

In addition, the realization of the convectionless conditions and precise control over fluid behavior required for many of the applications described above will require a great deal of work devoted to understanding the spontaneous motions that can occur in weightless fluids. Such motions can be driven by surface traction generated by surface tension variations, by volume changes, by intentionally applied forces in levitation apparatus, by electrical transport effects, and even by spacecraft accelerations in large fluid masses or special configurations. Not all of these motions will necessarily be deleterious; for example, it will probably be desirable to exploit them in cases where it is necessary to stir levitated melts to homogenize them or promote heat transfer from the interior to the surface. Because of their intrinsic interest as well as their applicability to the rest of the space processing experiment program, such fluid motions seem sure to comprise an active field of study in their own right.

Finally, support of other experiment areas will also require work in a variety of other physical process areas, such as wetting effects, methods of achieving thorough fluid mixing, means of removing gases evolved in melts, etc.

#### DISCIPLINE OBJECTIVES FOR THE 1980's

The Space Processing Program's goal of commercializing products manufactured in space can only be attained if private organizations come to foresee such concrete benefits to themselves in the Shuttle/Sortie Lab system's capabilities that they will be willing to invest their own resources in space research, development, and manufacturing. Accordingly, the essential role of NASA-sponsored activity will be to make space accessible to entry by private investment and to induce such investment by demonstrating that there is a reasonable prospect for commensurate returns.

At present we cannot be certain how much must be demonstrated to bring private capital to bear in amounts large enough to create space manufacturing businesses. Conceivably, the early years of Shuttle operations might produce such striking research results that industry would take over research and development very rapidly leaving NASA to continue only such work as was desirable for public purposes. On the other hand, the course of the program might be such that industry would adopt an extremely cautious attitude and remain unwilling to invest until NASA had actually demonstrated one or more viable space products in pilot manufacturing operations. There is also, of course, a whole spectrum of possibilities between these extremes, as well as a chance of outright failure.

In view of these uncertainties, the Space Processing Program office has adopted the following set of six objectives for the 1980s, which sketch the

necessary course of development from the beginning of Shuttle operations to the initiation of commercial manufacturing operations.

1. Make space easily accessible to the international scientific and industrial community for research and development work in materials science and technology.
2. Develop techniques that take full advantage of the characteristics of space flight to achieve experimental and process conditions that are not obtainable at competitive costs on Earth.
3. Employ the novel materials research and development techniques that are possible in space to acquire new knowledge in technologically important areas of materials science and technology.
4. Apply R&D results obtained in space to advance materials technology generally and, in particular, to invent processes to manufacture products in space for use on Earth.
5. When appropriate, reduce selected space manufacturing processes to practice and conduct pilot production operations to demonstrate their practicality.
6. When capabilities to manufacture economically viable products are achieved, initiate commercial production operations in space.

It is clear that the first of these steps must be accomplished by NASA and the last, by private industry, but that the four intervening steps might come about in many different ways. Naturally, it is to be hoped that the transition from public to private investment will be early and rapid. However, the program plans set out below are based on the conservative assumption that the first five of the above objectives must be accomplished primarily by Government-supported effort.

#### SUMMARY PROGRAM PLAN

The Space Processing Program's plans for accomplishing the objectives stated above fall into the four phases which follow:

##### INITIATION (Objectives 1 and 2)

With the resumption of manned space flights in the late 1970s, the program's primary tasks will be to introduce the scientific and industrial materials R&D

community to the technical opportunities offered by space, and also to develop techniques for materials R&D work that take full advantage of those opportunities.

The limited precursor experiments that will have been accomplished on the Skylab and the Apollo-Soyuz Test Program (ASTP) missions will provide a group of up to 20 scientists and engineers with some practical experience of materials work in space. However, in the early years of the new flight program, it will be necessary to build up a user group of at least 100 participating scientists and engineers, both to make reasonable progress toward the program's objectives and to achieve full utilization of the Space Shuttle's resources.

Therefore, much of the program's space activity in the early years of Shuttle operations will comprise preliminary experiments by materials scientists and engineers who are new to space work. Much of this work will involve the development and refinement of experimental methods and apparatus, and we expect that the average experimenter will require time on several flights to complete his research program.

#### RESEARCH AND DEVELOPMENT (Objectives 3 and 4)

Within a few years, the program is expected to reach a state in which large numbers of scientists and engineers are involved in its space activities and techniques are well established in its major areas of effort. Additions of new participants are then expected to fall to a rate about equivalent to the attrition rate due to completion of closed-end research projects. At that time effort devoted to new techniques and apparatus will drop to the level dictated by requirements that cannot be met by previously established methods.

The distribution of effort between materials research and process development will be largely determined by the interests of participating scientists and engineers in this period, since the program's principal needs will be to stabilize the user group recruited in the previous phase and to foster creative work that can lead to economically viable space manufacturing products and processes.

#### REDUCTION TO PRACTICE (Objective 5)

At some point in the middle 1980s, the program should have identified some space manufacturing products and processes with enough potential to warrant trials of production operations. It is possible that commercial entrepreneurs may wish to invest in this activity; but it seems more likely that the initial

trials must be wholly or largely funded by NASA, because they will break new ground in equipment development and space operations.

We expect that about three years will be required to develop and shake down the integrated space and ground facilities needed for pilot production of one or a few initial products. Thereafter, pilot-scale production will continue until full-scale production operations begin or decisions are made not to continue with non-viable products.

During this period, R&D activities are expected to continue at a level of effort at least as high as that established during the preceding phase.

#### COMMERCIAL PRODUCTION (Objective 6)

By the end of the 1980s, we hope to have demonstrated that full-scale space manufacturing operations will be commercially feasible for at least one product or process. It is expected that private investment will enter the picture in significant amounts during the late stages of pilot operations and that preparations for the first production operations will include only as much Government investment as is appropriate to NASA's role as a developer of space technology.

It should be noted that initiation of full-scale manufacturing operations will not supersede either R&D activities or pilot production operations. In fact, the levels of effort in both categories will probably increase and involve a rising proportion of private investment when it becomes evident that space manufacturing is practical and profitable.

#### THE SHUTTLE SORTIE MODE'S POTENTIAL CONTRIBUTIONS TO SPACE PROCESSING PROGRAM PLANS AND OBJECTIVES

In general, we believe that the Space Shuttle's seven-day sortie missions can provide a highly versatile and effective means of carrying out the first two phases (Initiation, and Research and Development) of the program's plans for the 1980s. At least the first part of the third phase (Reduction to Practice) can be accomplished on 30-day missions, but the late stages of pilot production and the initiation of the Commercial Manufacturing phase will probably require Shuttle-supported continuously operating orbital spacecraft.

#### EARLY PHASES

Through the first two phases of effort described above, the Shuttle will serve the program most effectively if it can provide very frequent flight opportunities for relatively small payloads.

Most of the program's participating investigators or R&D teams are expected to engage in continuing projects in the following general areas:

- Metallurgy
- Crystal Growth
- Glass and Ceramic Technology
- Biological Applications
- Physical Processes in Fluids
- Chemical Processes

Within each area different investigators will have many common equipment requirements, and different areas will also share some requirements. The Space Processing Program proposes to meet these requirements by building up an inventory of modular, general purpose equipment that can be configured flexibly to meet the needs of all participants with minimum additions of special fixturing for particular experiments.

However, during the early period of Shuttle operations the program will have to expand its user group considerably and support its users' work on developing effective methods for materials R&D in space. Although the program's foreseeable equipment requirements will be studied extensively during the 1970s, the amount of actual space data available for such studies will be very small compared to what can be derived from even the first year of Shuttle operations. Since new users are likely to develop many fresh requirements in their early efforts on the Shuttle, the most effective and economical course will be:

- To develop only enough equipment before the first Shuttle flights to engage the interests of users and support their initial experiments, and
- To carry on apparatus development concurrently with the Shuttle experiment program so as to build up an inventory of equipment that supports users' current needs.

Under this policy, the program's payload equipment inventory will evolve continuously toward increased capabilities, and the apparatus to be provided at the outset will be planned mainly to furnish satisfactory initial conditions for the evolutionary process that is to follow.

Thus, the Space Processing Program will begin the period of early Shuttle operations with a group of equipment that can be assembled in many different ways to make up payloads serving different needs, but the whole collection will probably not be large enough to make up a full payload for a dedicated sortie mission. In addition, the program will be seeking to serve a very diverse and rapidly



growing user group whose members will have little in common initially except pressing needs for early flight opportunities.

It will be extremely important to make flight opportunities easily accessible to the user community early in the Shuttle flight program, in order to attract materials scientists and engineers into space work and enable them to get satisfactory results without long delays and excessive coordination requirements. This can be accomplished most easily if the program takes advantage of the flexibility of its equipment to configure partial payloads for flight on substantially all of the early Shuttle missions.

Current planning literature suggests that on many (if not most) of its missions the Shuttle will fly with rather large weight margins, and we expect that further operations planning will show that many missions will also have significant crew timeline margins within the nominal seven-day mission duration. This seems especially likely on missions where the Shuttle functions as a launch vehicle and may have to remain on station with its daughter spacecraft during extensive ground-controlled checkout periods.

Because of the very diverse nature of its subject matter, the program can probably provide experiment payloads that would be compatible with virtually any primary Shuttle payload and could make nearly full use of the Shuttle's residual resources on any mission. Naturally, it will be most economical to provide payloads for manned operation in most areas of interest. However, some types of experiments, such as diffusion controlled crystal growth from solutions, may require such long times and low acceleration levels that they must be performed on free-flying unmanned satellites. Also, if the available carrying capacity furnishes a sufficient incentive, it should even be feasible to assemble automated payloads that could operate in unpressurized bay space with their own power sources and radiators.

We therefore propose that the Space Processing Program should utilize every Shuttle flight as if it were a sortie mission, whether the flight carries a Sortie Lab or not. If the Shuttle proves to be sufficiently flexible for this mode of operation, the program can gain access to the frequent flight opportunities and payload space required by its objectives, virtually without impact on the Shuttle's ability to meet other programs' requirements.

Highly frequent flights of relatively small space processing payloads early in the program will afford many opportunities for hardware economy, maximize users' flight opportunities, and help to maximize utilization of the Shuttle. In addition, the program will have enough flexibility in this mode of operation to exchange Shuttle payload space and mission time with other disciplines that may

need to fly equipment either earlier or later than originally anticipated. In effect, therefore, the program can act as a kind of "flywheel" to help ensure that the Shuttle can fly on a regular schedule with full payloads, in spite of the multiple contingencies that will affect payload availability.

At some point in the Research and Development phase described above, we expect that the program's user community and apparatus technology will mature to the point where dedicated sortie missions will become the most efficient mode for its further operations in some areas. The total level of effort in space will probably exceed the equivalent of more than one dedicated mission per year when this point is reached, and much of this activity is likely to involve sharing of Sortie Lab space with other disciplines. Therefore, the initiation of dedicated sortie flights will involve a reorganization of some of the program's space activities rather than an expansion of effort.

The transition to dedicated sorties will probably come when the program has grown to include substantial process development activities aimed at demonstrating the feasibility of specific products. This type of effort can operate on the somewhat rigid schedules we foresee for dedicated missions more easily than can exploratory research, which must work more or less at its own pace to be most effective. Thus, the first dedicated flights will probably be organized mainly for process development. On the other hand, the dedicated missions will have specially trained payload specialists, and this will be a considerable advantage for the more sophisticated types of research experiments. We therefore expect that the program's early dedicated missions will include some research activities, although the bulk of its research will probably continue to use shared space on other missions to gain the advantages of high flight frequency.

Adequate flight frequency can be obtained with dedicated missions if the program's total effort rises to a level that can use, say, three or four sorties per year. As long as the maximum mission duration remains at seven days, however, the cost advantages of sharing space on other missions will probably cause the program to restrict its dedicated mission activity to those cases where resource requirements exceed what can be obtained on shared missions.

With the advent of thirty-day missions, the cost effectiveness situation may alter in favor of dedicated sorties. By this time the program's apparatus technology will have matured enough so that much of its research equipment will be in routine use without needing frequent modification. The user community will probably have stabilized as well, so that most participants will be engaged in long-term projects that can function effectively with flights on a prescribed schedule. Many of the program's process development activities will

have reached the point where refinement of process conditions rather than basic equipment development is their main concern. Thus, the program may have developed the capacity to use thirty-day missions effectively at about the time when they become feasible, and in this event their cost advantages over multiple seven-day missions will become overriding. In addition, sortie missions sponsored by the other disciplines are likely to have much less payload space available for sharing when those disciplines go over to thirty-day mission durations.

## THE PHASE OF REDUCTION TO PRACTICE

The program's pilot production operations will begin when processes are fully developed for some highly promising products and the question of their economic viability must be settled. It is highly unlikely that this question can be answered for any product by production on a laboratory scale, because manufacturing costs and operating procedures can only be defined with sufficient precision by operations on a scale approximating what is necessary for commercial production.

These considerations will apply with special force to space manufacturing, where previous commercial experience will provide next to no guidance on a wide variety of crucial questions. In order to manufacture finished products that involve processing in space, it will be necessary to set up ground facilities to prepare materials for space processing, orbital facilities to carry out the process steps that must be performed in space, and ground facilities to finish the space-processed materials and integrate them with other components of the final product. The operation of all these facilities must be integrated, which will pose many unusual problems in production scheduling and material flow, equipment maintenance, procurement and marketing, and even labor relations. In addition to settling these operational issues, the pilot production operations must validate a wide variety of technical choices made during the development period, such as equipment designs, the degree of manned involvement in production processes, safety provisions, etc., before the commitment to full-scale facilities is made. And finally, the features of government-industry relations that affect operating costs will require trial production operations for their accurate assessment.

With so many questions to be settled, it is not to be expected that initial pilot plant operations will be routine or quickly concluded. Several short missions will probably be required to check out and shake down pilot space facilities before production runs can begin, and production will probably have to proceed for some time before the combined space and ground facilities begin to operate

smoothly enough together to yield convincing information on operating economics and the products' ability to meet market price and performance requirements.

Dedicated Shuttle sortie missions are likely to provide the best means of performing equipment shakedown runs and intermittent operations to make ready for consistent pilot production, but it is not certain that missions with a thirty-day time limit can adequately support actual production. If continuous output is a necessity, the completion of pilot operations may have to wait until it becomes possible to place production facilities permanently in orbit.

## THE COMMERCIAL MANUFACTURING PHASE

At this point it is impossible to foresee very clearly just what space manufacturing operations will be like. Conceivably they might be supported by sortie missions if the associated ground operations could work with intermittent supplies of space processed materials and if the space processes involved relatively large amounts of material and physically small processing equipment. However, it appears more probable that most processes will work most economically with highly automated continuously operating facilities in orbit, using the Shuttle to transport personnel, supplies, and processed materials.

Thus, it seems likely that the Space Processing Program may be among the first to generate firm requirements for a permanent orbital Space Station. In its early years of operation, this station may be too small to require full Shuttle payloads for its logistic support, so that visits would be needed from the Shuttle on missions flown for other purposes. Because of this, the station may develop a subsidiary function as a way-station to "warehouse" hardware that is used in orbit but does not need to be returned to the ground after every use. Ultimately, however, manufacturing operations in orbit are expected to build up a factory complex large enough to require regular dedicated sortie missions to service them. The space factory will probably have passed into full private ownership by then, and its dedicated logistic service seems likely to become a commercial operation within a few years of its initiation.

## RECOMMENDED POLICIES AND PROCEDURES FOR SHUTTLE UTILIZATION

### ALLOCATION OF PAYLOAD SPACE

Since economical operation of the Shuttle will depend to a large extent on its maintaining a regular schedule with full payloads, the Shuttle program should

be primarily responsible for space allocations and flight scheduling. In line with this responsibility, it should keep all of the discipline program offices informed on a current basis of mission launch dates and resources currently available on each future flight. Payload scheduling and priorities should be periodically reviewed by an Agency-wide Shuttle Missions Board having the authority to resolve conflicts between program offices or direct changes to reflect national policy, but actions to obtain flight assignments should be handled directly between the discipline program offices and the Shuttle program.

#### ACCEPTANCE OF EXPERIMENTS FOR FLIGHT

Flight opportunities will cease to be uniquely valuable events when the Shuttle reaches operational status. Therefore, the decision to develop and fly particular experiments should rest with the discipline program offices under control exercised by the cognizant Associate Administrators through the budgeting process.

#### FLIGHT QUALIFICATION

The responsibility to qualify experiments and apparatus for flight on the Shuttle should rest with the organization (which may not be a NASA program office) seeking space on the Shuttle. This responsibility should be considered to have been met if the proposed payload passes acceptance tests prescribed by the Shuttle program.

#### PRIVATE USE OF THE SHUTTLE

As early as possible, services by the Shuttle should be made available to private organizations that are willing to pay their fair shares of mission costs. Private requests for Shuttle services should be subject to competent review by Agency management, but organizations whose requests are approved should not be subject to any extra qualification requirements and should receive full title to any results they obtain from their space activities.

#### ESTIMATED SIZE OF THE SPACE PROCESSING PROGRAM USER COMMUNITY

The user community in the fields covered by the Space Processing Program is potentially enormous since it includes materials scientists and engineers of all descriptions. Involvement can be expected from many areas, ranging from

pharmacology to ferrous metallurgy, and it will be worldwide. In quantitative terms, it can be pointed out that in the United States alone there are upwards of 90,000 chemists, including 15,500 on the faculties of colleges and universities, approximately 12,000 physicists in materials related fields, 13,700 members of the Metallurgical Society, and 6000 in the American Ceramic Society. On a worldwide basis, it seems conservative to estimate that the program's Shuttle activities will touch the professional interests of between 200,000 and 300,000 scientists and engineers, and the technology interests of virtually every materials related industry.

As we have pointed out above, direct participation in the Shuttle program will involve only a small fraction of this group and is likely to take several years to develop fully after flights begin. However, the published work of the direct participants in the program will reach the entire community outlined above. If all goes well, we can expect this work to show the international scientific and industrial community that the Shuttle represents a resource for new materials technology that no organization can afford to ignore. As this realization becomes widespread, it could conceivably create a demand for the Shuttle's services far exceeding the most optimistic of current projections.

#### INTERFACES WITH THE USER COMMUNITY

In the early phases of Shuttle operations, space processing experiment activity will be strongly oriented toward research and development, most of which will be Government funded until such time as the promise of space manufacturing is proved sufficiently to attract private investment. Therefore, the program will have much of the character of normal Government supported R&D with a rather high usage of GFE facilities, the only material difference being that some of the facilities will be in space.

User interface procedures for this kind of activity are well developed and will need only one major change to adapt them for efficient Shuttle utilization. The Space Processing Program will serve as a discipline oriented sponsoring office to solicit experiment proposals, select experiments to be performed, and sponsor supporting research and development. In view of its plans to use its apparatus repeatedly for different experiments and its need for continuous apparatus development, the program should also be responsible for developing all of the payload apparatus required for its activities. Thus the Shuttle program's relation to the Space Processing Program would be that of a supplier of space transportation services to a user organization with needs for such services; we recommend that this relation should be governed by the policies and procedures outlined in the preceding section on that topic.

As the Space Processing Program progresses toward pilot production operations, some of its space activities are likely to take on the character of cooperative ventures with industry. Arrangements for such joint programs will have to be defined on an Agency wide basis by NASA's legal and policy-making bodies, and it is to be hoped that a suitable background of administrative precedent will evolve out of the conduct of relatively small scale joint experimental activities before the need for pilot production operations arises.

We recommend that the Space Processing Program should act in the capacity of NASA's agent to make the direct arrangements for cooperative projects in its discipline area, and that its interface with the Shuttle program in these cases should be the same as in projects that are wholly Government funded. On the other hand, it seems appropriate that any industrial user organization wishing to fly its own payloads wholly at its own expense should deal directly with the Shuttle program on an independent basis. In such cases the program should act only as a source of any technical advice the Shuttle program might need, and should not be called upon to perform any functions that would compromise the outside user's proprietary interests.

The same considerations would apply to full-scale production operations. If such operations are a joint venture between NASA and another user organization, then the user interface should be handled between the Space Processing Program and the Shuttle program. If production is undertaken independently by a non-NASA organization, however, that organization should deal directly with the Shuttle program to obtain the latter's services.

#### RECOMMENDATIONS TO THE SHUTTLE PROGRAM

The following actions on the part of the Shuttle program are recommended to support implementation of the plans outlined above:

1. The Shuttle's payload accommodations should be designed to that worthwhile corollary payloads can be carried to utilize the vehicle's residual resources on missions where the prime payload leaves significant margins. Since most of the development and operating costs of the Shuttle will be associated with its ability to lift weight into orbit, consideration should be given to organizing on-board utilities such as power, data systems, radiators, etc. so that the full lifting capacity can always be utilized.
2. In its design work and operational planning, the Shuttle program should ensure that each of the discipline offices is aware of what is being done

to meet all of the others' requirements, so that they can assess potential conflicts and will be made aware of the full range of flight opportunities that may be available.

3. Beginning early in both programs, the Shuttle and Sortie Lab contractors should be directed to assign liaison engineers to keep the discipline offices informed of work in progress, so that the latter can express their concerns over developing problems or recommend action to grasp unforeseen opportunities to the NASA Shuttle program management on a timely basis.
4. In order to serve space processing users effectively, the Shuttle should be designed so that it can provide acceleration levels no higher than  $10^{-4}$  g in normal operations and can control accelerations to levels below  $10^{-6}$  g by special operations.
5. An early decision should be made regarding responsibilities for discipline payload equipment development, so that the individual discipline offices can begin to make firm plans for their SRT and payload development programs for the 1970's.

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## APPENDIX A

### SPACE PROCESSING PAYLOADS

#### PAYLOAD ELEMENT DESCRIPTIONS

Our analysis of the need for the Space Processing Program to support a large and very diverse user group has led to the conclusion that the program should seek to obtain very frequent flight opportunities for partial shuttle payloads, rather than widely spaced dedicated Sortie missions. Accordingly, the payload elements described below are conceived as partial payloads to be flown in conjunction with payloads flown for other programs. Identical payload element descriptions have been submitted by the Space Processing Program office for inclusion in the January, 1973 revision of the NASA Mission Model.

Four types of payloads are envisioned for the program. These are based on groups of experiments with similar equipment and support requirements. Each will consist of modular equipment configured to perform as many experiments as possible within the resources available on the mission where it flies. Therefore, a range of values is given for the size, weight and power consumption of each payload element, corresponding to that element's range of possible configurations.

Where possible, the equipment will be designed to be capable of autonomous operation in unpressurized payload bay space on missions where carrying capacity is the only available resource. Therefore, the set of payload elements includes a rack on which experimental apparatus can be mounted in the bay. For planning purposes, pending development of further data, it should be assumed that the Furnace and Levitation units described below can be flown either in pressurized or unpressurized space, but that pressurized space is preferred. Since flight of any of these units in unpressurized space would require mechanized manipulations, the weights of such payloads should be assumed to be in the upper halves of the ranges specified for these units. At present we anticipate that the biological unit and general purpose unit would be operated only in a pressurized Sortie lab. Three modes of operation should be considered in structuring payload flight programs for space processing:

- Payload elements flown singly or in combination within the Sortie Lab.
- The furnace and/or levitation unit flown on the pallet.
- The furnace and/or levitation unit flown on the support unit.

The estimated characteristics of the program's payload elements are as follows:

#### FURNACE UNIT

- Weight: 200 to 500 kg
- Size: 1.5 to 3.0 cubic meters
- Power Consumption: 2.0 to 5.0 kw

This type of payload will be designed to implement experiments of the general class represented by Skylab experiments M555 through M566, where the principal requirement is for heat treating in a weightless environment without extensive manipulations of levitated samples. The main processing equipment in such payloads will be electric furnaces with their associated measurement, control and power conditioning equipment. The furnaces themselves will be physically small and will have rather widely varying power requirements depending on their temperature capabilities and special features. Each furnace payload will include several different types of furnace in its equipment complement, selected on the basis of current experiment needs and available mission resources.

#### LEVITATION UNIT

- Weight: 500 to 1000 kg
- Size: 2.0 to 5.0 cubic meters
- Power Consumption: 2.0 to 10.0 kw

Payloads of this class will be designed to implement experiments involving detailed high-temperature manipulations of levitated melts, such as glass formation, ultrapurification by zone refining or evaporation, crystal growth from levitated melts, or experiments with supercooled melts. Three or four levitation units with special capabilities for these different types of work will be available in the Space Processing Program's inventory. Power requirements will vary from about 1 to about 5 kw, depending on designed temperature limits and sample sizes, and they should be flown in combination with each other because of their common need for a high-frequency power supply, as well as similarities in measurement and control systems.

## BIOLOGICAL UNIT

- Weight: 300 to 700 kg
- Size: 2.0 to 5.0 cubic meters
- Power Consumption: 1.0 to 3.0 kw

Payloads for experiments on preparation and purification of biological materials will have little equipment commonality with other space processing experiments and therefore form a class by themselves. Equipment available to form such payloads will include three or four systems for separation by electrophoresis and its variants, two experimental incubation systems, and ancillary equipment for sample handling and preservation, preparation of chemical solutions, and measurement and control.

## GENERAL PURPOSE UNIT

- Weight: 100 to 500 kg
- Size: 0.5 to 3.0 cubic meters
- Power Consumption: 0.3 to 3.0 kw

Payloads in this class will comprise diversified equipment for experiments on topics such as fluid heat flow and convection, process simulation, crystal growth from aqueous solutions, and aspects of physical chemistry. High temperatures will generally not be required for such work and most of the required power will be used by measurement and control systems. Since this type of payload can easily be broken down into small sub-units, it will be natural to fly appropriately configured versions with other payloads in order to make sure of using all available resources.

## SUPPORT UNIT

- Weight: 500 kg
- Size: 17 cubic meters

This class of unit is not conceived as a payload in itself, but rather as a means of providing needed support to other space processing payloads when the Shuttle

functions as a launch vehicle. The basic unit would be a cylindrical rack structure about one meter long and with the maximum diameter that will fit the payload bay. This structure would weigh about 500 kg. and any space processing equipment to be carried in the payload bay would be mounted on it on missions where the Sortie Lab pallet was not available. The cylindrical configuration was selected so that the rack could be mounted in one end of the bay, leaving a maximum of free bay length for satellite deployment payloads.

## ENGINEERING CHARACTERISTICS

The experiment and sensor content of each payload element is summarized and numerical data on size, weight, and usage of crew time, electric power, and heat rejection are collected in Table A-1. More detailed engineering estimates are currently being prepared for the program by the TRW Systems Group under Contract No. NAS8-28938, Requirements and Concepts for Space Processing Payload Equipment, and the program will also make use of assistance from the Shuttle System Payload Data Study.

## INTERFACE REQUIREMENTS

Where possible, space processing payload equipment should be located at or close to the vehicle center of gravity in order to minimize acceleration levels. As noted above, the interface between the equipment and the Shuttle system may be provided by the Sortie Lab, the pallet associated with it, or a special equipment rack. It is expected that the program's equipment will be launched in operating configurations so that the only storage requirements will be for experimental samples and consumables.

The payload elements described above will have no requirements for special support equipment such as airlocks, optical windows, stable platforms or booms. However, studies are currently planned on the feasibility of providing an ultrahigh vacuum environment for some experiments by deploying a shielding device to sweep out a void in the ambient gas around the Shuttle. If these studies show that the method is worth using, a requirement will be generated for an appropriate deployment capability either for a boom-mounted device or a free-flying facility.

At this time it does not appear that the payloads envisioned here will require checkout support or special controls and displays to be provided by the Shuttle/Sortie Lab system. Unless further study of the whole payload picture reveals a significant degree of equipment commonality with other programs, it would be preferable for the program to install its equipment in a "bare" Sortie Lab or pallet containing only utility connections.

**Table A-1**  
**Engineering Characteristics of Space Processing Payloads**

SUBELEMENT	WEIGHT POUNDS	VOLUME FEET <sup>3</sup>		METALLURGICAL		CRYSTAL		GLASS		BIOLOGY		PHYSICAL		CHEMICAL		TOTAL SUBELEMENT
				PER RUN	PER MISSION	PER RUN	PER MISSION	PER RUN	PER MISSION	PER RUN	PER MISSION	PER RUN	PER MISSION	PER RUN	PER MISSION	
<b>FURNACE</b> ENCLOSURES & HEATERS FURNACES (HOT WALL) COOLING EQUIPMENT MIXING & DISPERSAL MANIPULATION/PLACEMENT TEMPERATURE MEASUREMENT ATMOSPHERIC CONTROL POWER CONDITIONING	440 TO 1100	80 TO 108	EXPERIMENT OPERATIONS		10		4		2							16
			CREW TIME HRS	1	10	3	12	1	2							24
			SUSTAINED POWER KW	6(2) *		6(2)		6(2)								6(2)
			TIME AT SUSTAINED POWER HRS	2	20	6	20	2	4							44
			ENERGY KWH	10	100	25	100	10	20							220
			PEAK POWER KW	10.5(8)		10.5(8)		10.5(8)								10.5(8)
			TIME AT PEAK POWER HRS	.2	2.0	.2	.8	.2	.4							3.2
			PEAK ENERGY KWH	2.1	21	2.1	8.4	2.1	4.2							33.6
			HEAT REJECTION X 10 <sup>3</sup> BTU	41.3	413	93.0	372.0	41.3 *	82.6							868
<b>BIOLOGICAL</b> COOLING EQUIPMENT OPTICAL EQUIPMENT BIOLOGICAL PROCESS EQUIPMENT TEMPERATURE MEASUREMENT SAMPLE PLACEMENT POWER CONDITIONING	900 TO 1840	70 TO 178	EXPERIMENT OPERATIONS								13					13
			CREW TIME HRS					0		.5	6.5					6.5
			SUSTAINED POWER KW							1.8						1.8
			TIME AT SUSTAINED POWER HRS							.75	10					10
			ENERGY KWH							1.3	18					18
			PEAK POWER KW							1.8						1.8
			TIME AT PEAK POWER HRS							.15	1.95					1.95
			PEAK ENERGY KWH							.29	8.7					3.7
			HEAT REJECTION X 10 <sup>3</sup> BTU							8.42	72.1					72.1
<b>LEVITATION</b> FURNACES (HOT WALL) ENCLOSURES HEATERS COOLING EQUIPMENT MIXING & DISPERSAL EQUIPMENT POSITIONING/MANIPULATION ATMOSPHERIC CONTROL TEMPERATURE MEASUREMENT POWER CONDITIONING	1100 TO 2200	70 TO 178	EXPERIMENT OPERATIONS		3		2		4			2			1	12
			CREW TIME HRS	1	2	1.5	3	2	0			1	2	1	2	18
			SUSTAINED POWER KW	6(4)		6(4)		6(4)				4(2)		3(1)		
			TIME AT SUSTAINED POWER HRS	3	0	4	0	3	12			1	2	1	1	32
			ENERGY KWH	18	54	24	48	18	72			4	8	3	3	183
			PEAK POWER KW	13(10)		13(10)		13(10)				8(8)		6(3)		13(10)
			TIME AT PEAK POWER HRS	.3	.0	.3	.0	.3	1.2			.2	.4	.2	.2	3.3
			PEAK ENERGY KWH	3.9	11.7	3.9	7.8	3.9	15.6			1.2	2.4	1.0	1.0	38.5
			HEAT REJECTION X 10 <sup>3</sup> BTU	74.5	223.5	95	190	74.5	298			17.8	35.6	13.5	13.6	760.7
<b>GENERAL</b> FURNACES HEAT EQUIPMENT TEMPERATURE MEASUREMENT SAMPLE PLACEMENT POWER CONDITIONING	220 TO 1100	18 TO 108	EXPERIMENT OPERATIONS									4		0		9
			CREW TIME HRS									2	0	2	10	18
			SUSTAINED POWER KW									1.7		1.7		1.7
			TIME AT SUSTAINED POWER HRS									4	16	4	20	28
			ENERGY KWH									6.8	27.2	6.8	34.0	61.2
			PEAK POWER KW									2.3		2.3		2.3
			TIME AT PEAK POWER HRS									2	0	2	10	18
			PEAK ENERGY KWH									4.6	18.4	4.6	23	41.4
			HEAT REJECTION X 10 <sup>3</sup> BTU									38.8	155.2	38.8	194	349

\*NOTE: VALUES IN PARENTHESIS INDICATE DERATED CAPABILITY.

1. EXPERIMENT OPERATIONS DENOTE MINIMUM RUNS PER MISSION

## ENVIRONMENTAL REQUIREMENTS

Unless the program develops requirements for external ultrahigh vacuum facilities or solar concentrators, its experiments will not be sensitive to the Shuttle's external environment. Many experiments will use vacuum apparatus that will be vented to space, but the internal cleanliness of this apparatus will be critical to the experiments, and it will be easy to insure that only oxygen, nitrogen, and inert gases are vented.

In general, a class 100,000 per cubic foot cleanliness level in the Sortie Lab is considered adequate for space processing experiments. Temperature excursions over a relatively wide range (approximately 10 to 45°C) should not affect the equipment when it is not in operation. During operation, however, some equipment will require stable ambient temperatures for optimum control and instrumentation accuracy, and therefore temperatures should be held within approximately  $\pm 1^\circ\text{C}$  limits during experimental runs.

The Space Processing Program's prime operational requirement is for a low acceleration environment, since all of its activities will be based on exploitation of the weightless conditions that are available in space. The sensitivities of different experiments to acceleration will vary widely, but the average experiment is expected to require that accelerations from all sources be held at or below  $10^{-4}$  g(i.e., about 0.1 cm/sec<sup>2</sup>).

Vibrations should be minimized, since vibration can have the same effects as linear acceleration would have on most experiments. Reasonable vibration levels should present no special problems during non-operating periods, however, since the equipment will be designed to withstand the launch vibration environment. During operating periods, experiments on crystal growth and separation of biological materials are expected to be most sensitive to vibration.

Space processing experiments should not be any more sensitive to electromagnetic interference than ordinary commercial laboratory equipment, but the payloads will include high frequency induction heaters and electromagnetic positioning equipment that may be potential sources of radio frequency interference. However, it is believed that proper shielding and isolation techniques can prevent this equipment from interfering with other experiments.

## ORBITAL CHARACTERISTICS

Experiments in the space processing program will have a general preference for high-altitude orbits of low eccentricity so that atmospheric drag and ambient gas densities will be minimized, and may sometimes require the Shuttle to fly in



whatever attitude minimizes drag accelerations. In addition, space processing payloads will tend to maximize heat rejection requirements, and if the Shuttle/Sortie Lab radiator system requires a special orientation under maximum load conditions it may usually be necessary to maintain that orientation.

Although the Space Processing Program has not yet adopted definite requirements for solar concentrators or vacuum wake shield devices, these would also have some influence on requirements for orbital characteristics. Solar concentrators would need to be used primarily in sun-synchronous orbits, and both types of systems would probably require special spacecraft orientations with stability of the order of one degree and durations of the order of hours.

### UTILITIES REQUIRED

Nominal power requirements are listed for space processing payload elements in Table A-1, but it should be borne in mind that each payload element will comprise multiple experiments using modular apparatus, so that great latitude will exist to adjust the total power consumption or heat rejection rates to fit available capacity. Since the experiments will tend to be heavy users of electrical power, the amounts of space processing equipment that can be included in any mission will probably be controlled by fuel cell and radiator capacity rather than weight and volume. Individual items of equipment may require a wide variety of different forms of electric power, and it is expected that the payload elements will include power conditioning equipment to perform required conversions on whatever forms are available on the Shuttle Sortie Lab system buses.

The prime sources of data for space processing experiments will be digital tape, still and motion picture film, and processed materials returned to Earth for analysis. Most data requirements can be met by returning records to Earth for post flight analysis, but two-way television might be needed for experiments where crew involvement was high and interaction was required with investigators on the ground. Except for possible TV requirements, the real-time data needs for space processing payload elements are expected to be low, probably not exceeding  $10^4$  bits per second, but any experiment requiring real-time data should be expected to last for several hours at least.

The payload elements are expected to require a rather large number and variety of programmed control functions even when their operation is not automated, and therefore each payload will incorporate a small general-purpose computer that will provide all necessary support and data processing functions. All data recorded during space processing experiments will need to be keyed to accurate times and measurements of rotation rates and accelerations in all six degrees

of freedom. Other housekeeping data will probably be needed as well and should be available on the Shuttle's data bus. We foresee no requirement for Shuttle-provided measurements of conditions outside the spacecraft.

In addition to real-time data, it would be convenient if the Shuttle data system could provide continuously updated forecasts of future maneuvers and of power and heat rejection capacity to the space processing payload's automatic control equipment. If these were available it would be comparatively simple to give the payload capabilities to schedule its activities for optimum resource utilization in real time.

Space processing payloads will also require many special types of consumables, including water, gases, etc. with specifications generally different from those of other payloads. It seems that it will be most practical to supply most of these from within the payload rather than the vehicle system, although of course maximum use will be made of system utilities where possible. Payloads mounted inside the Sortie Lab will require low-impedance vacuum connections to the exterior environment. Four-inch vacuum lines will probably be adequate, and at least six ports should be provided for exterior connections.

## CREW SUPPORT

Summary numerical data on crew time utilization are given in Table A-1 for space processing payload elements operating in non-automated modes. At the level of detail covered in the present document it seems unrealistic to specify duty cycles of preferences for single or multi-shift operation, because these choices would be arbitrary. As operational planning proceeds we expect it to become clear how crew time should be organized to maximize the output of experimental results from each mission.

The Space Processing Program's early experiments are expected to consist mainly of the application of prescribed procedures to samples of material supplied by investigators, requiring only simple setups of apparatus in flight and no alterations of experiment protocol during any single run. As is the case in the program's Skylab experiments (M551 through M566), process conditions during most experimental runs will be under automatic programmed control, and practically all handling of the apparatus and samples would be within the capabilities of a simple tape-controlled industrial manipulator. Full automation of the program's early experiments would therefore be a feasible option. It is expected to be cheaper to design the apparatus to be set up and reconfigured as necessary by the Shuttle crew, however, since only simple mechanical skills will be required for the early experiments.

Requirements for manned involvement are likely to increase as the program's experiments increase in sophistication and its experimenters learn to use the crew's services resourcefully. Two-man experiment support crews will probably suffice for most missions, but some extremely diversified dedicated payloads may require up to four men to exercise all of their equipment fully.

In all operations we can visualize at present, the role of payload specialists in space processing experiments will be to act as skilled laboratory technicians rather than as primary investigators. It may prove worthwhile to qualify some investigators who are deeply involved in developing new techniques to fly so that they can gain first-hand experience of the Shuttle's operating environment, but for other purposes trained astronauts will be the better bargain.

#### MISSION REQUIREMENTS

Estimates of the numbers for flights that will be required for the Space Processing Program in the 1980s are given in Appendix C.

#### GROUND OPERATIONS SUPPORT

The only special prelaunch problems foreseen for space processing payloads will occur in dealing with perishable biological samples, which will generally require storage at temperatures of  $-20^{\circ}\text{C}$  or lower and need to be loaded in the Shuttle on the day it is launched. However, it should also be borne in mind that the program will serve on the order of 100 principal investigators, of whom as many as 20 or 30 may have samples of some kind on any given flight that carries a payload element for the program. Attention should therefore be given to pre- and post-flight sample handling procedures that will minimize delays in their work, since most investigators will be engaged in projects involving multiple flights.

## APPENDIX B

### USER PAYLOAD ELEMENTS

Although the Space Processing Program has not reached the stage where firm requirements can be specified for payload elements to be flown on the Shuttle by private users, some of their needs are approximately foreseeable. The following discussion was prepared for the 1973 NASA Mission Model, and is included here for the information of users of the present report.

The basic intent of the Space Processing Program is to stimulate space research and development activity financed by users and conducted by them in their own behalf as early as possible in the Shuttle program. User activity of this sort will probably develop gradually over the early years of Shuttle operations, and initially it is expected to focus on experiment operations similar to those conducted in the NASA program and using similar apparatus. In fact, since NASA will have an inventory of general-purpose apparatus available, the first user-sponsored experiments are likely to rent NASA equipment within the payload elements described above in order to avoid apparatus development costs.

As their interests become more specific and specialized, users will probably find it necessary to develop their own apparatus. However, until some users begin pilot production operations, we do not expect user-sponsored activities to require individual payload elements as large as those described for the NASA program. In the years immediately preceding the start of pilot production, space processing payload elements flown on the Shuttle will probably comprise mixtures of NASA and private equipment being employed for private experiments. Therefore, at the level of detail appropriate for this revision of the mission model, user activity prior to initiation of pilot operations can be represented adequately by flight of payload elements with the same gross characteristics as the NASA elements.

When pilot production begins, users will require new types of payload elements with detailed characteristics dictated by the nature of the production processes involved. We cannot foresee many of these details, because the products and production processes involved will not be defined until user R&D activity on the Shuttle has made considerable progress. On the other hand there is a reasonable basis for estimates of gross characteristics for two types of pilot production payload. These are given below:

#### LIGHT MANUFACTURING MODULE:

- Weight: 1000 kg

- Size: 5.0 cubic meters
- Power Consumption: 10-20 kw

This payload element represents the type of equipment that would be used for pilot operations involving small amounts of material and products of such high value that they could be manufactured profitably on Shuttle Sortie missions. The full-scale production facility for which this module is the pilot plant is visualized as making up a full Sortie mission payload and the size and weight given are chosen to make the pilot plant about 1/5 the size of the full-scale one. Since this payload element would be flown primarily for engineering purposes, we estimate that it would require a payload support crew of two men from the user's organization.

#### HEAVY MANUFACTURING MODULE:

- Weight: 5000 kg
- Size: 30 cubic meters
- Power Consumption: 20-50 kw

This payload element is visualized as a pilot plant for a large space factory of a type that could only be established in a continuously operating space station complex. The payload has been sized to fill a Sortie lab completely and would require a support crew of two men. It might be carried on one or two Sortie missions for test purposes, but operational use would require it to fly continuously in conjunction with the Space Station. Therefore this type of module should not be included as a pilot plant in mission models that exclude the Space Station. On the other hand, its gross characteristics are probably about right for a full-scale plant whose pilot plant is represented by the Light Manufacturing Module.

## APPENDIX C

### SPACE PROCESSING ESTIMATES OF PROGRAM MISSION REQUIREMENTS

Mission models for the payload elements described in Appendices A and B have been developed by the Space Processing Program office for the January, 1973 revision of the NASA Mission Model, with and without the assumption that a Space Station will be established in 1986. The desired flight frequencies estimated for the several payloads are summarized in Tables C-1 and C-2, and the rationale for the estimates is outlined below.

In both cases, we visualize an early buildup of NASA-sponsored activity, followed after an interval of a year or two by user-sponsored activity which will increase at a somewhat slower rate and concentrate on development of specific processes and early introduction of pilot production operations. In addition, flights are indicated for 1979 in both cases, on the ground that it would be useful for the Space Processing Program to test its critical equipment items in space before extensive experimentation begins, and the test flight of the Shuttle might be employed for this purpose.

In the case where the Space Station is excluded we believe that user interest in Space processing will be weighted toward performing applied research for the benefit of technology on the ground. Any manufacturing operations that may be undertaken in this case will necessarily involve intermittent production and relatively high costs per unit of time in orbit so that the only feasible products will be ones that use small amounts of material, have exceedingly high value, and require only short processing times.

In view of these stringent requirements for profitability we believe that users will be relatively cautious in their approach to space if there seems to be no prospect of getting continuously orbiting facilities. We therefore estimate a lower level of user activity for the case excluding the station than for the case including it, and expect that pilot manufacturing operations for the first space product are not likely to begin before the end of the decade.

For the Space Station case, it is assumed that experiment activity will build up to a high level before 1986 in an effort to prepare for initiation of pilot production operations soon after the station is established. While most experiment activity will shift to the station as soon as its payload is operational, we also foresee a continuing need for occasional Shuttle missions to perform tests with developmental equipment that is not ready for installation in the station. These flights are included in the attached tables, but logistic missions to support the Space Processing Program's operations on the station are not.

We believe that user-sponsored activity will increase more rapidly if a Space Station is planned than if it is not, and that pilot manufacturing operations will begin sooner because of the station's superior operating economy from the investor's standpoint. Small scale operations of the sort represented by the Light Manufacturing Module will probably come first because they are likely to involve the least business risk, but it seems reasonable to assume that the first Heavy Manufacturing Module might be launched at the end of the decade. As in the case of the NASA program, logistic flights in support of private Space Station activities have not been included in the table.

Table C-1

Mission Model Summary of 1978-1990 Missions,  
Excluding Space Station

NASA SPACE PROCESSING PROGRAM	79	80	81	82	83	84	85	86	87	88	89	90
Biological Unit	1	2	3	4	4	4	4	4	4	4	4	4
General Purpose Unit	1	2	3	3	4	4	4	4	4	4	4	4
Furnace Unit	1	4	4	4	4	4	4	4	4	4	4	4
Levitation Unit	1	2	3	4	4	4	4	4	4	4	4	4
USER-SPONSORED MISSIONS (Additional to NASA missions listed above)*												
Biological Unit				1	1	1	2	2	2	3	3	3
General Purpose Unit							1	1	1	1	1	2
Furnace Unit						1	1	1	2	2	2	2
Levitation Unit					1	1	1	2	2	2	3	3
Light Manufacturing Module											1	2

\*Flights of units with the same names as NASA payload elements are to be understood as private levels of activity in the corresponding area, which may use equipment that is either privately owned or rented from NASA. In either case, the gross characteristics of NASA payload elements should be used for mission modeling.



Table C-2

Mission Model Summary of 1979-1990 Missions,  
Including Space Station

NASA SPACE PROCESSING PROGRAM	79	80	81	82	83	84	85	86	87	88	89	90
Biological Unit	1	2	3	4	5	6	6	2	1	1	1	1
General Purpose Unit	1	2	3	3	4	4	4	1	1	1	1	1
Furnace Unit	1	4	4	4	6	6	6	6	1	1	1	1
Levitation Unit	1	2	3	4	6	6	6	2	1	1	1	1
Station Modules    1								△	_____			
2										△	_____	
USER SPONSORED MISSIONS (Additional to NASA Missions listed above)*												
Biological Unit			1	2	2	3	3	2	1	1	1	1
General Purpose Unit					1	1	1	1	1	1	1	1
Furnace Unit				1	1	2	3	2	1	1	1	1
Levitation Unit			1	1	2	2	3	2	1	1	1	1
Light Manufacturing Modules												
Sortie Missions								1		1		
Installed in Station										1		1
Heavy Manufacturing Module												1

\*Flights of units with the same names as NASA payload elements are to be understood as private levels of activity in the corresponding areas, which may use equipment that is either privately owned or rented from NASA. In either case the gross characteristics of NASA payload elements should be used for mission modeling.

APPENDIX D

REPORTS AND STUDIES ABOUT  
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Chronologically Listed

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